MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963

ADA040028

MULTI-LAYER MODEL
OF
In As EPILAYERS

(12)

H. A. WASHBURN

**DEPARTMENT OF PHYSICS
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO 80523**

D D C

RECEIVED

MAY 31 1977

A.

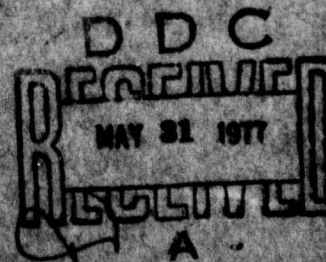REPORT SF IT

FILE COPY

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER SF 11	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Multi-Layer Model of InAs Epilayers.		5. TYPE OF REPORT & PERIOD COVERED Technical Report.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) H. A. Washburn		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0976
9. PERFORMING ORGANIZATION NAME AND ADDRESS Colorado State University Fort Collins, Colorado 80523		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task NR 372-305
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Electronics Program 800 N. Quincy, Arlington, VA 22213		12. REPORT DATE April 15, 1977
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 15 Apr 77		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

16 p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Indium Arsenide
Interfaces
Semiconductors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The charge carrier transport coefficients of an inhomogeneous, thin semiconductor in an indium arsenide MOS structure were obtained using a multilayer model. The expression for the Hall coefficient of a three-layer system extended to arbitrary strength magnetic fields was used to separate the bulk transport parameters from the parameters describing transport at the two surfaces. Experimentally, a gate voltage was used to vary the surface under the oxide from depletion to accumulation and the Hall coefficient measured as a function of magnetic field.

DD FORM 1473 1 JAN 73   EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

MULTI-LAYER MODEL OF InAs EPILAYERS

H. A. WASHBURN

PHYSICS DEPARTMENT

COLORADO STATE UNIVERSITY

FORT COLLINS, CO.   80523

SUMMARY

The charge carrier transport coefficients of an inhomogeneous, thin semiconductor in a MOS structure were obtained using a multi-layer model. The expression for the Hall coefficient of a three-layer system extended to arbitrary strength magnetic fields was used to separate the bulk transport parameters from the parameters describing transport at the two surfaces. Experimentally, a gate voltage was used to vary the surface under the oxide from depletion to accumulation and the Hall coefficient measured as a function of magnetic field. The characteristics of the back surface were obtained with the front surface held at the flatband condition. The variation of the front surface parameters with gate voltage was obtained with the front surface in accumulation. The measurements were made on a MOS structure consisting of an InAs epilayer deposited by VPE procedures on a semi-insulating GaAs substrate covered by a pyrolytic silicon dioxide insulating layer and aluminum gate.

I. INTRODUCTION

InAs epilayers grown by VPE procedures on semi-insulating GaAs substrates have exhibited nearly bulk-like electrical characteristics[1,2,3] even though there is about a 7% lattice mismatch between the two materials and the front surface, whether free[3] or covered with an oxide[2], is normally accumulated. The InAs-GaAs interface has been shown to have a compositionally graded region[4] and the front surface is thought to contain a combination of fast and slow surface states[5]. It is thus expected that the carrier density and mobility in the epilayers will exhibit spatial inhomogeneities in the direction perpendicular to the film.

In order to understand the electrical transport in these epilayers and the influence of spatial inhomogeneities, a model of the epilayer is presented (see fig. I(c)) which assumes three parallel, non-interacting layers: a region with bulk-like properties bounded by a front surface layer (surface I) and an interface layer (surface 2). The magnetic field dependence of the Hall coefficient calculated for this model, when combined with the gate-voltage control of surface I from accumulation through flatband condition into depletion, provides a means of determining the transport parameters for the three layers. The advantage of the present method is the additional information obtained, non-destructively, about the transport coefficients in the InAs-GaAs interface region.

2. THEORY

A schematic of the three-layer model is shown in Fig. I (c). The Hall coefficient for arbitrary magnetic field strength and an arbitrary number of parallel, non-interacting layers has been derived[6,7]. For the case of three layers with predominantly one carrier type (in the present case, electrons)   it is given by

$$R_h(B) = \frac{\frac{d}{e} X_2}{(X_1^2 + X_2^2) B} \tag{1}$$

where

$$X_1 = \sum_{i=1}^{3} \frac{n_i d_i \mu_i}{1 + \mu_i^2 B^2} \qquad , \qquad X_2 = \sum_{i=1}^{3} \frac{n_i d_i \mu_i^2 B}{1 + \mu_i^2 B^2} \quad ,$$

$n_i d_i$ is the carrier density per unit area of the ith layer, μ_i is the corrseponding Hall mobility, B is the magnetic induction normal to the plane of the epilayer, and $d = \sum_{i=1}^{3} d_i$ is the film thickness. In the following, the subscripts $i \equiv s1,b,s2$ will be used, corresponding to surface 1, the bulk-like layer, and the interface layer respectively.

For a given carrier density at surface 1 the limiting values of Eq. (1), R_{ho} and $R_{h\infty}$ for $B \to 0$ and $B \to \infty$ respectively, the value of the magnetic induction, $B_{\frac{1}{2}}$, for which $R_h(B_{\frac{1}{2}}) = \frac{1}{2}(R_{ho} + R_{h\infty})$, and the conductance, σ_o, at $B = 0$, can be used to determine[3] the parameters $n_b d_b$ and μ_b of the bulk-like layer and another set of parameters, $\langle n_s d_s \rangle$ and $\langle \mu_s \rangle$, which describe a high carrier density, low mobility layer and are assigned to net surface parameters assumed to include the effects of both surface 1 and surface 2. Namely, it is assumed

$$\langle n_s d_s \rangle = n_{s_1} d_{s_1} + n_{s_2} d_{s2} \tag{2}$$

$$\langle \mu_s \rangle = \frac{n_{s_1} d_{s_1} \mu_{s_1} + n_{s_2} d_{s_2} \mu_{s_2}}{\langle n_s d_s \rangle}$$

Varying the carrier density, and thereby the carrier mobility, of surface 1 causes a variation in the net surface parameters which

can be observed by measuring the conductivity and the Hall coefficient as a function of magnetic field. In particular, when surface 1 is brought into flatband condition $n_{s1}d_{s1} = 0$ and the ~~effective~~ net surface parameters in Eq. (2) reduce to $n_{s2}d_{s2}$ and μ_{s2} respectively.

It should be noted that at flatband there is remaining in the surface layer a carrier density corresponding to the bulk level. This yields a density per unit area which is comparatively small and its effect can be formally included in the bulk layer's parameters.

3. EXPERIMENTAL PROCEDURES

The InAs epilayers were 15μm thick and were grown by chemical vapor phase transport on semi-insulating GaAs substrates[1,2,8]. A silicon dioxide insulating layer about 2000 Å thick was deposited by the low temperature pyrolysis of silane and aluminum gates were deposited which covered the entire "active" area of the devices as shown in Fig. 1(a) and 1(b). The measurements reported in subsequent figures were obtained from a low carrier density bridge shaped sample at 77K, Fig. 1(b), although measurements on cloverleaf samples, Fig. 1(a), and other samples which had only partial gate coverage gave qualitatively similar results.

The capacitance-voltage measurements were similar to those obtained by others[5] in that the flatband condition occurs for large negative gate voltages and appreciable hysteresis is present. All measurements reported were made as a function of decreasing gate voltage, each voltage setting being held until equilibrium was reached. This often took about 15 seconds for voltages in the depletion region. Flatband gate voltage was found[9] from the extrapolated intercept of $\left(\dfrac{C_{ox} - C}{C} \right)^2$ versus $(V_g - V_{ox})$ where the oxide capacitance was determined in the full accumulation region. For the present sample $V_{FB} = -46$ V.

The conductance and Hall coefficient were measured as functions of gate voltage and magnetic field using constant d.c. applied currents of 100µA or 1 mA. Gate voltages were derived from a battery and voltage divider and magnetic fields were obtained from a superconducting magnet or, for B < 10 kguass, from a standard electromagnet. All voltage measurements were made using $4\frac{1}{2}$ or $5\frac{1}{2}$ digit digital voltmeters with input impedances > 10^{10} ohms.

4. RESULTS AND DISCUSSION

The Hall coefficient as a function of magnetic field is shown in Fig. 2 for two representative gate voltages, one (-45 V) near flatband, the other (+40 V) in the full accumulation region. The net surface parameters as described above were calculated for each gate voltage and are given in Fig. 3. The carrier densities and mobilities at the front surface derived from the data in Fig. 3 using Eq. (2) are shown as the open circles in Fig. 4. The bulk layer, the interface layer, and the front surface for $V_g > V_{FB}$ are all n-type.

From Fig. 3 it is noted that the carrier density and mobility for $V_g < V_{FB}$ are essentially constant. This is in agreement with the model since in this gate voltage region the front surface is in depletion and thus contributes little to the transport. Thus, according to the three-layer model presented above, the effective surface parameters in this gate-voltage region are due to electrons in the InAs-GaAs interface layer. Since $n_{s_2} d_{s_2} = <n_s d_s>_{FB}$ and $\mu_{s_2} = <\mu_s>_{FB}$ the data in Fig. 3 give $n_{s_2} d_{s_2} = 2.23 \times 10^{13}$ cm^{-2} and $\mu_{s_2} = 2.29 \times 10^3$ cm^2/V-sec. It is thought that the large carrier density and low mobility in the interface region is due to defects resulting from the lattice mismatch. The parameters determined for the bulk layer are $n_b = 1.17 \times 10^{15}$ cm^{-3}

and $\mu_b = 1.22 \times 10^5$ cm^2/V-sec.

Fig. 4 exhibits the expected results when the front surface is in full accumulation[10]. That is, for increasing accumulation the carrier density increases and the mobility decreases. Perhaps not obvious from Fig's 3 and 4 is the fact that the carrier density from flatband to about −30 V, while changing very little, nevertheless increases monotonically. The front surface mobility, μ_{s_1}, in Fig. 4 exhibits a maximum near −32 V and then decreases as V_g approaches V_{FB}. While this behavior was observed in most of the samples measured, it is not considered conclusive since the accuracy with which μ_{s_1} is calculated from Eq. (2) depends on $n_{s_1} d_{s_1}$ which near flatband approaches zero. Further, $\langle n_s d_s \rangle$ is determined by the high magnetic field saturation value of the Hall coefficient[3], $R_{h\infty}$, which as seen in Fig. 2, has not been reached at B = 60 kgauss and must be obtained by extrapolation of the R_h versus B curves. Thus the dependence of $\langle n_s d_s \rangle$, and consequently $n_{s_1} d_{s_1}$ which is obtained by simply subtracting $n_{s_2} d_{s_2}$ from $\langle n_s d_s \rangle$, on V_g is essentially that observed at 60 kgauss and may, in fact, change at higher fields thus appreciably affecting μ_{s_1} near flatband.

Also plotted in Fig. 4 are the values for the front surface parameters obtained using the gate voltage dependence of the zero field limit of the Hall coefficient and conductivity[7]. This method uses a two-layer model in which the bulk and the interface are combined and described by one set of parameters. The good agreement of the front surface parameters obtained from these two analytical methods tends to support the applicability of the three-layer model to the InAs epilayers. The agreement is particularly remarkable since the use of high magnetic fields should require the consideration of interactions between layers, multi-band effects, and spatial inhomogeneities in directions other than normal to the plane of the film[11].

The solid lines in Fig. 2 were calculated from Eq. (1) using the parameters derived above for the appropriate gate voltages. The calculated curves describe the general behavior of the $R_h(B)$ data although the data are more "smoothed out". A general result is that the three-layer model can be made to fit the data better than the two-layer model[12], particularly in the high field region. The next logical step is to use many layers, such as by profiling the interface region with a quasi-continuous density and mobility distribution, to provide a better fit to the $R_h(B)$ data. This has been done with an attendant improvement in the fit to the data[12], but the validity of any such modeling requires independent confirming evidence.

In the analysis of the data it has been assumed that the bulk layer thickness is much larger than the thickness of either surface layer. The front surface should have a thickness on the order of a Debye length, which for these InAs epilayers at 77K is about 600Å. The interface layer thickness is not known. The compositionally graded region is about 1500 Å thick[4], but if the carrier density is primarily due to defects[13] and assuming the defects propogate somewhat into the epilayer then there may not be a correspondence between the composition gradient and the electrical gradient. Thickness dependence measurements of the electrical properties[12,13] have not been able to determine the interface layer thickness except to estimate an upper limit of about 3 μm.

5. CONCLUSIONS

The Hall coefficient and conductivity of InAs epilayers have been measured as a function of gate voltage and magnetic field and have been analyzed in terms of a three-layer model. The agreement of the results for the front surface carrier densities and mobilities as a function of

gate voltage with those obtained by a more conventional method confirm
that the three-layer model is a reasonable approximation to the spatial
inhomogeneities present in the InAs epilayers.

REFERENCES

1. J. P. McCarthy, Solid-State Electron., 10 (1967) 649.

2. H. H. Wieder, Appl. Phys. Lett., 25 (1974) 206.

3. J. R. Sites and H. H. Wieder, CRC Crit. Rev. Solid State Sci., 5 (1975) 385.

4. N. K. Wagner, Thin Solid Films, 38 (1976) 353.

5. R. J. Schwartz, R. C. Dockerty, and H. W. Thompson Jr., Solid-State
    Electron., 14 (1971) 115.

6. A. Nedoluha and K. M. Koch, Z. Phys., 132 (1952) 608.

7. H. H. Wieder, Thin Solid Films, accepted for publication.

8. The samples used in this work were kindly provided by H. H. Wieder and
    the Naval Electronics Laboratory Center, San Diego.

9. K. Ziegler and E. Klausmann, Appl. Phys. Lett., 26 (1975) 400.

10. A. Many, Y. Goldstein, and N. B. Grover, Semiconductor Surfaces,
    North-Holland, Amsterdam, (1967) Chpt. 8.

11. A. C. Beer, Galvanomagnetic Effects in Semiconductors, in Solid State
    Physics edited by F. Seitz and D. Turnbull, (1963) Chpts VI and X.

12. H. A. Washburn and J. R. Sites, Bull. Amer. Phys. Soc., 22 (1977) 318.

]3. B. J. Baliga and S. K. Ghandhi, J. Electrochem. Soc., 121 (1974) 1646.
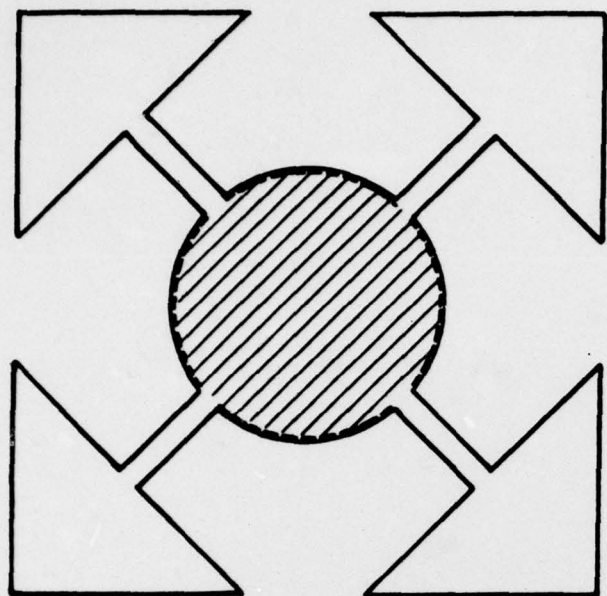
FIGURE CAPTIONS

Figure 1.   Sample configurations, (a) cloverleaf and (b) six-arm bridge, with the gate area cross-hatched. (c) Cross-section of the sample including schematic representation of the three layers used to model the epilayer.

Figure 2.   Magnetic field dependence of the absolute value of the Hall coefficient. The open circles are data points for the two indicated gate voltages, each set being connected by the dashed curves. The solid lines are calculated from the three-layer model.
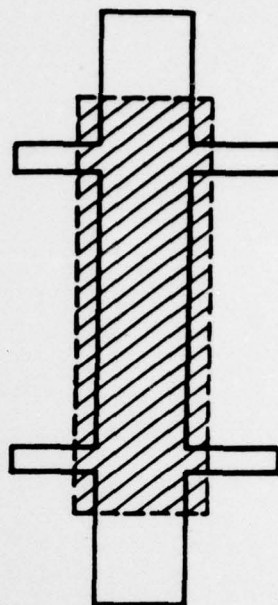
Figure 3.   Net surface carrier density and carrier mobility versus gate voltage.

Figure 4.   Front surface carrier density and carrier mobility versus gate voltage. The open circles were obtained from the three-layer model, the solid circles were obtained from a low-field two-layer method[7].
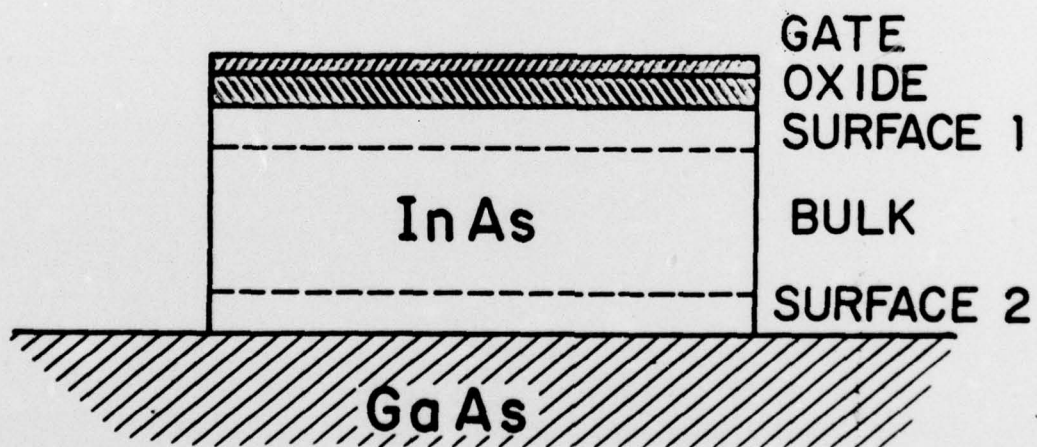
(a)

(b)

GATE
OXIDE
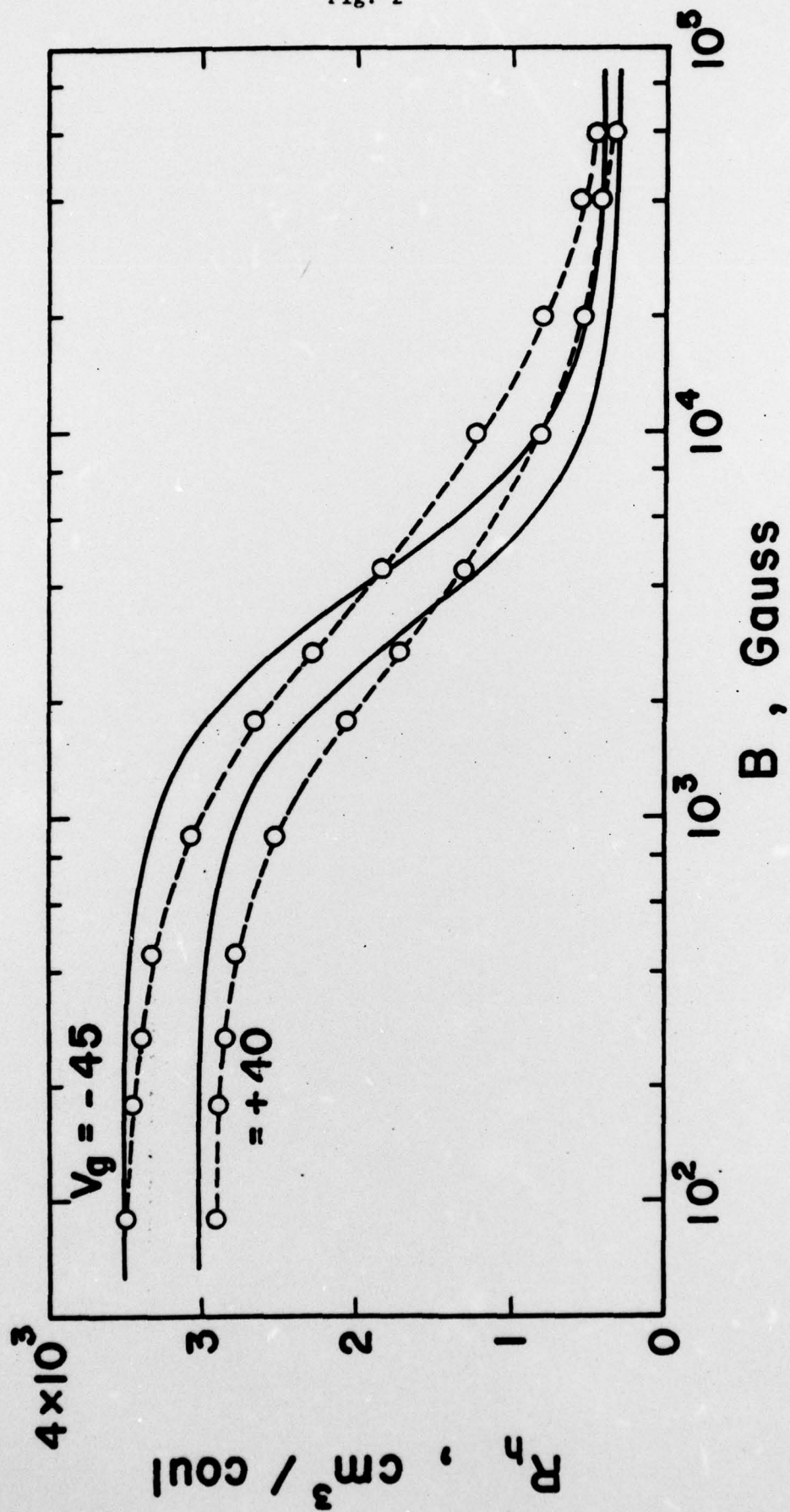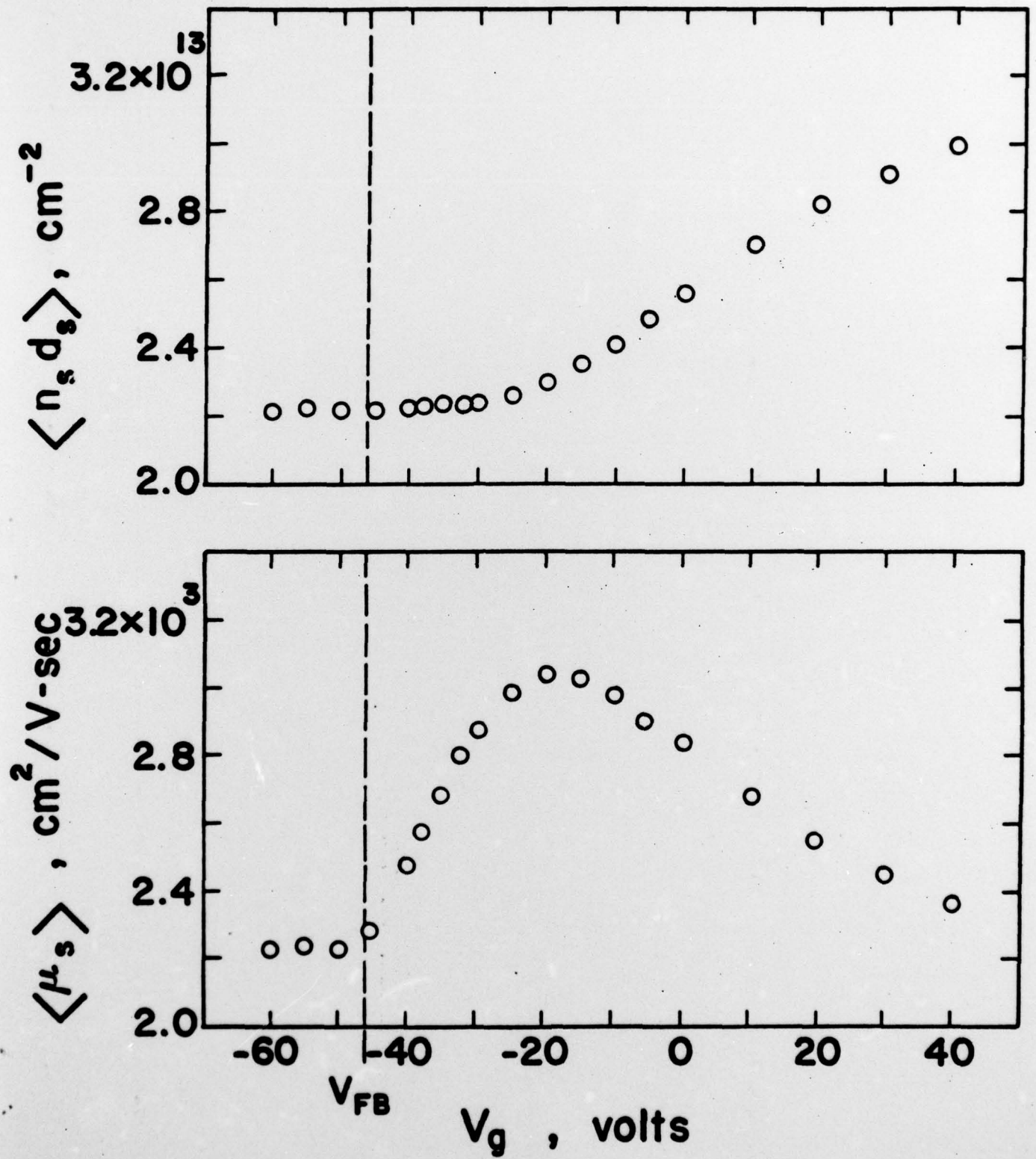SURFACE 1

In As   BULK

SURFACE 2

Ga As

(c)

Fig. 1

Fig. 2

Fig. 3

Fig. 4